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Publication Date
2016-08-08

DOI
10.1061/9780784480137.005

Peer reviewed

Impact of Long Term Temperature Cycling on Thermo-Hydro-Mechanical Behavior of Unsaturated Soils Surrounding an Energy Pile

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ABSTRACT: This paper describes a numerical investigation into the thermo-hydro-mechanical response of unsaturated soil surrounding an example energy pile subjected to two different seasonal temperature fluctuations over five years. Long-term temperature cycling was observed to lead to a progressive zone of drying around the energy foundation and a corresponding decrease in hydraulic and thermal conductivity values. A larger decrease in degree of saturation was observed for temperature fluctuations from 0 to 45 °C than for temperature fluctuations from 5 to 25 °C. Further, a larger decrease in degree of saturation was found for soils with lower initial degree of saturation. In the example evaluated in this study, the decrease in degree of saturation was relatively small, but is still associated with a decrease in long term heat exchange efficiency as well as increased effective stress in the soil, which may affect the intended performance of the energy pile. The example presented in this study may help guide site-specific evaluations to evaluate this behavior.

1. INTRODUCTION

Energy piles are a well-established technology to exchange heat with the subsurface (Brandl 2006; Laloui et al. 2006). There have been several recent studies on their thermal properties measured using thermal response tests, and thermo-mechanical behavior under different boundary restraints and cyclic heating and cooling. However, there have not been many studies on their long-term performance under seasonal temperature fluctuations, which in the continental U.S. typically range from approximately 5 to 35 °C (Murphy and McCartney 2015). Wider temperature ranges may be encountered in more extreme climate settings or in settings dominated by heating or cooling. This study is focused on the observations from the numerical simulation of the behavior of energy piles in unsaturated soil layers. The reason for the focus on this particular soil setting is that changes in the long-term thermo-hydro-mechanical behavior of unsaturated soils may be expected during heating and cooling cycles. It is well known water will flow away from an available heat source if subjected to a thermal gradient (Philip and de Vries 1957; Cary and Taylor 1962; Milly 1982; Thomas and Sansom 1995). Further, changes in degree of saturation will lead to a decrease in the thermal conductivity (Lu et al. 2010a; Smits et al. 2013), a decrease in the hydraulic conductivity (van Genuchten 1980), and an increase in the effective stress (Lu et al. 2010b) of unsaturated soils. Due to these coupled thermo-hydro-mechanical behaviors, a progressive zone of drying and densification may occur around the energy pile that may need to be considered in their design.

2. BACKGROUND

In the presence of a temperature gradient, water will move from regions of high temperature to regions of low temperature in both liquid and vapor phases. Vapor transport is primarily a diffusive process resulting from the development of a vapor pressure gradient in response to a thermal gradient. Liquid water is observed to flow from areas of warm to cold due to the presence of a surface tension gradient, as the surface tension of water in contact with air increases with decreasing temperature. As the matric suction, ψ, also increases with decreasing temperature, a suction gradient within the soil may also contribute to thermally-induced liquid water flow (Cary 1966). Previous studies have defined the coupled governing equations for coupled flow of liquid water, water vapor, and heat (Philip and de Vries 1957) as well as the analytical and numerical solutions to these equations (Cary and Taylor 1962; Milly 1982; Thomas and Sansom 1995). These solutions have also been extended to incorporate the volume change response of a deformable soil to the coupled flow of heat and water (Thomas and He 1995). McCartney (2012) described experimental evaluations of thermally induced water flow in sand and clay, and noted that the zone of influence for thermally induced water flow is a function of initial saturation, hydraulic conductivity, thermal conductivity, and porosity, a greater zone of influence is expected for silts or clays of low plasticity with a higher initial degree of saturation.

The hydraulic conductivity of unsaturated soils will vary as a function of the soil solid pore network (i.e., porosity or void ratio), the properties of the pore fluid (viscosity) and the amount of pore fluid within the system (i.e., the degree of saturation or water content). The hydraulic conductivity of unsaturated soil will decrease with decreasing saturation due to a reduction in the water pathways required for water to flow out of the soil. The effective degree of saturation S_e (i.e., the degree of saturation normalized by the residual degree of saturation) is related to the matric suction via a soil specific relationship referred to as the soil water retention curve (SWRC). van Genuchten (1980) developed a smooth hyperbolic function for the SWRC that can be fitted to experimental ψ-S_e data points, along with an approach to estimate the hydraulic conductivity as a function of the effective saturation for an unsaturated soil from the fitting parameters of the SWRC (van Genuchten 1980).

The effective stress in unsaturated soils is closely linked with the hydraulic behavior of the soil. Bishop (1959) defined the effective stress of unsaturated soils as:

$$\sigma' = (\sigma - u_a) + \chi (u_a - u_w) = \sigma_n + \chi \psi \tag{1}$$

where $\sigma_n = (\sigma - u_a)$ is the net stress, $\psi = (u_a - u_w)$ is the matric suction equal to the difference in pore air and water pressures, and χ is an effective stress parameter. The effective stress approach relies heavily on the definition of χ, which is related to the soil's structure and degree of saturation. Lu et al. (2010b) proposed that the value of χ is equal to S_e, which permits the van Genuchten (1980) SWRC specific to a given soil to be incorporated into the definition of the effective stress. In this case, changes in ψ or S_e lead to changes in effective stress in the soil, which may result in changes in volume or shear strength.

3. MODELING OF THERMALLY-INDUCED WATER FLOW

Vadose/W© 2007 was used to model the thermally induced water flow as a result of the long-term thermal cycling of a hypothetical energy foundation. Wilson et al. (1994) provides a detailed discussion on the theory utilized by the software; however, a brief summary is described herein. The water and heat mass transfer equations utilized in Vadose/W© 2007 are derived from the one-dimensional Richards' equation for transient flow in unsaturated soils with adaptations for vapor flow added by Wilson (1990). The partial differential equation for this case is given as follows:

$$\frac{1}{\rho}\frac{\partial}{\partial z}\left(D_v \frac{\partial P_v}{\partial z}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial (P/\rho g + z)}{\partial z}\right) + Q = \left(C_S + L\frac{\partial \theta}{\partial T}\right)\frac{\partial P}{\partial t} \tag{2}$$

where P is the absolute water pressure, P_v is the vapor pressure, k_z is the hydraulic conductivity of the unsaturated soil in the z-direction obtained from the hydraulic conductivity function, Q is a boundary flux, D_v is the vapor diffusion coefficient, z is the elevation head, ρ is the density of water at a temperature (T), g is the acceleration due to gravity, C_s is the volumetric heat capacity of unsaturated soil obtained from a volumetric heat capacity function, L is the latent heat of vaporization of water, θ is the volumetric water content, and t is time. The partial differential equation governing one-dimensional heat flow in unsaturated soils is given as follows:

$$L\frac{\partial}{\partial z}\left(D_v \frac{\partial P_v}{\partial z}\right) + \frac{\partial}{\partial z}\left(k_{tz} \frac{\partial T}{\partial z}\right) + \rho_c v_z \frac{\partial T}{\partial z} + Q_t = \left(C_S + L\frac{\partial \theta}{\partial T}\right)\frac{\partial T}{\partial t} \tag{3}$$

where ρ_c is the volumetric specific heat value, k_{tz} is the thermal conductivity of the unsaturated soil in the z-direction obtained from a thermal conductivity function, v_z is the Darcy velocity of water in the z-direction, and Q_t is the thermal boundary flux.

Considering that the governing equations for heat and water flow contain three unknown variables: P, T, and P_v, Vadose/W incorporates the following relationship between absolute pressure and the vapor pressure, as follows:

$$P_v = P_{vs} \cdot e^{\frac{-P \cdot w}{\rho \cdot R \cdot T}} \quad \textbf{(4)}$$

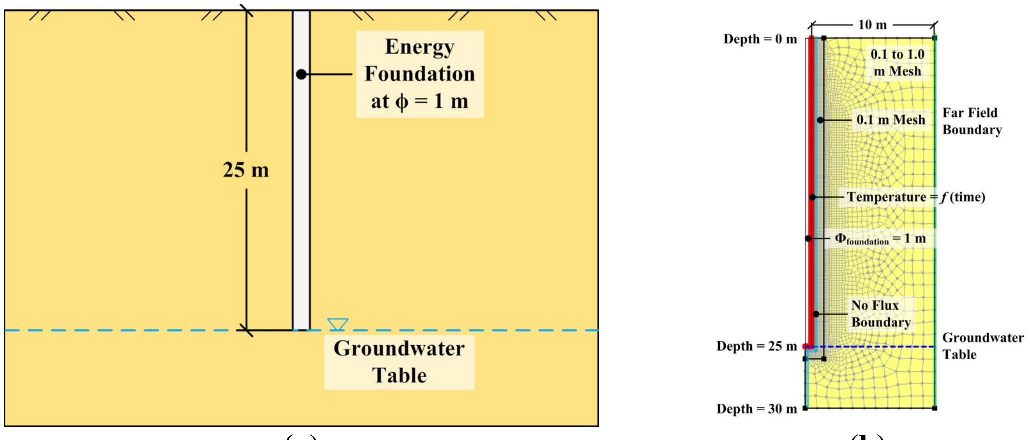
where P_{vs} is the saturated vapor pressure of pure free water, w is the molecular mass of water vapor, and R is the universal gas constant. Use of this equation permits the two coupled governing equations to be solved simultaneously.

For this paper, the properties of Bonny silt were chosen to highlight the impact of long-term temperature cycling on the thermo-hydro-mechanical response of an unsaturated soil surrounding an energy pile. For a "Full Thermal" analysis, Vadose/W© requires the SWRC, a hydraulic conductivity function (HCF), a thermal conductivity function (TCF), and a volumetric heat capacity function (VHCF) for the soil modeled. The SWRC was represented using the model of van Genuchten (1980), which was fitted to experimental data obtained by Khosravi and McCartney (2012). The hydraulic conductivity, thermal conductivity, and volumetric heat capacity functions were defined using the models of van Genuchten (1980), Johansen (1975), and Johnston et al. (1981), respectively, which are implemented through sub-modules provided within the program. Table 1 summarizes the key properties of Bonny silt required for these models for a dry density of 1.5 Mg/m^3 and a porosity of 0.41.

Table 1: Properties of Bonny silt used in the VADOSE/W analysis

van Genuchten (1980) SWRC Model Parameters	a	28.571	kPa	**Specific gravity**	G_s	2.54	-
	n	1.77	-	**Thermal Strain Rate**	ε_{Tz}	0.0015	%/°C
	θ_s	0.41	-	**Cohesion**	c'	0	kPa
	θ_r	0.04	-	**Friction Angle**	ϕ'	32.4	°
Thermal Conductivity of Soil	k_{tz}	121.8	kJ/(day·m·°C)	**Thermal Conductivity of Water**	k_w	52.27	kJ/(day·m·°C)
Vol. Heat Capacity of Soil	C_s	1840	kJ/(m^3·°C)	**Vol. Heat Capacity of Water**	C_w	4187	kJ/(m^3·°C)
Sat. Hydraulic Conductivity	k_s	8.64×10^{-3}	m/day	**Latent Heat of Water**	L	2260	kJ/kg

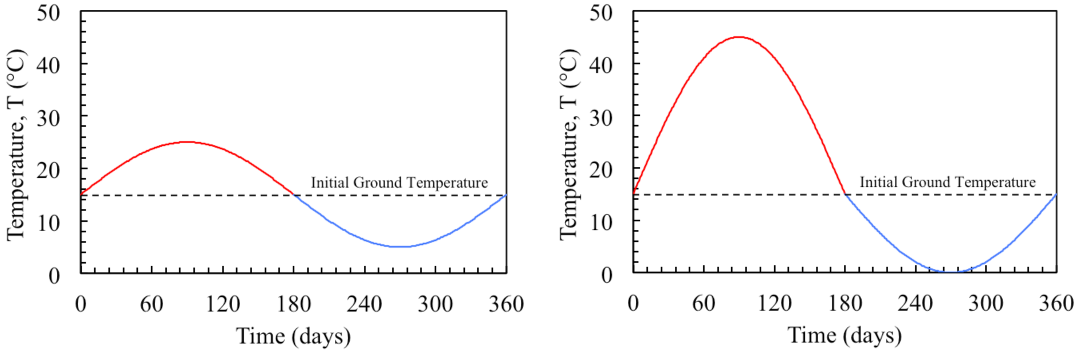
The influence of long-term temperature cycling on the surrounding soil of a 1-m diameter, 25-m deep energy pile shown in Fig. 1(a) was analyzed in this study. The particular dimensions are typical of energy piles encountered in the field (Brandl 2006; Laloui et al. 2006; Murphy and McCartney 2015). The groundwater table was selected to be located at the toe of the energy pile and the unsaturated zone above the groundwater table is assumed to satisfy initially hydrostatic conditions. Axisymmetric models are the best choice for modeling the behavior of a cylindrical deep foundation, but this option is not available in Vadose/W© 2007. Accordingly, the energy pile was modeled as a 2-dimensional half space as shown in Fig. 1(b). Despite this modeling simplification, the flow processes in the soil are still approximately representative of that surrounding an energy pile. The 25 m energy pile is underlain by 5 m of silt with 10 m of silt set to the right side. Preliminary analysis indicated this range to be large enough to avoid any undesired boundary effects while maintaining reasonable program run times during analysis. Furthermore, infinite elements were included at the right of the problem geometry to simulate a "far field" boundary as indicated in Fig. 1(a) by a green boundary. Inclusion of the infinite elements helps simulate an infinite boundary to the right of the hypothetical energy pile to avoid any influence of the model boundary.



(a) **(b)**

Fig. 1. (a) Schematic of Problem Geometry; (b) Schematic of Mesh, Initial Conditions, and Boundary Conditions for Energy Pile Model

The immediate 1 m zone surrounding the energy pile was meshed with a combined quadrilateral-triangular grid at a maximum size of 0.1 m. Outside the finely meshed region, a 0.1 to 1.0 m gradient quadrilateral-triangular mesh is applied. This meshing regiment allowed Vadose/W$^{©}$ 2007 to model the thermally induced water flow immediately surrounding the foundation without loss of detail. An initially constant earth subsurface temperature of 15 °C was selected which reflects the conditions of most non-tropical climates (Brandl 2006). Two sinusoidal energy pile temperature fluctuations were considered in this study, shown in Figs. 2(a) and 2(b). Case 1 involves a temperature range of 5-25 °C typical of an energy pile in a temperate climate, while Case 2 involves a temperature range of 0-45 °C for extreme conditions. Case 2 was used investigate the influence of heightened thermal swings on the thermo-hydro-mechanical response of the soil in comparison with that from Case 1. Application of these thermal cycles were applied at the boundary of the energy pile as indicated in Fig. 2(b) by the red line. Finally, a "no flux" hydraulic boundary condition, indicated by a blue line in Fig. 1(a), was applied along the energy foundation so that no water flow could occur into the energy pile during analysis.



(a) **(b)**

Fig. 2. Energy Pile Yearly Temperature Cycles: (a) Case 1; (b) Case 2

Prior to application of any thermal cycles, the 30 m soil profile was allowed to reach hydrostatic conditions based on a groundwater table located at a depth of 25 m. The resulting initial saturation and matric suction profile is shown in Fig. 3. Based on the groundwater location at a depth of 25 m, degrees of saturation along the soil-structure interface ranged from 1 to nearly 0.25. After hydrostatic conditions were reached, thermal cycles were applied at the boundary of the energy pile for 1800 days at time increment of 18 days. No infiltration of water occurs during the heating period, which is representative of energy piles covered by an impermeable slab.

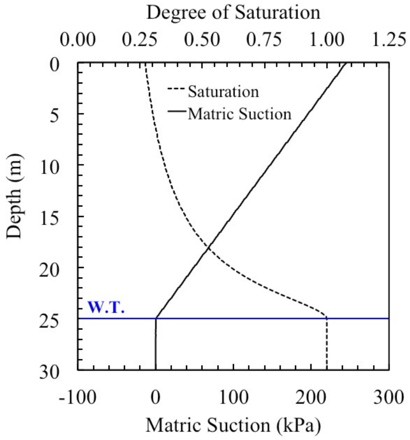
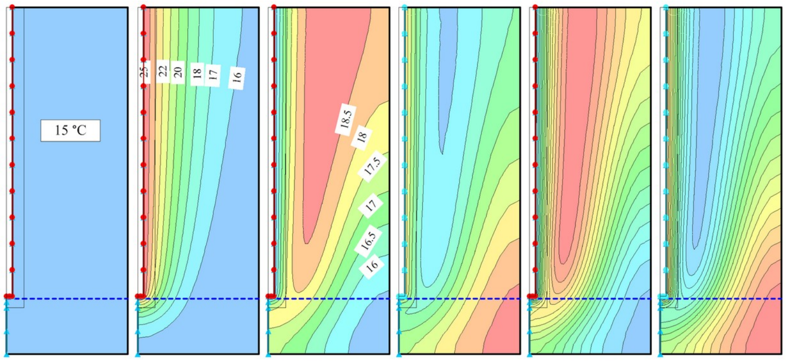


Fig. 3. Initial Profiles of Degree of Saturation and Matric Suction

4. SIMULATION RESULTS

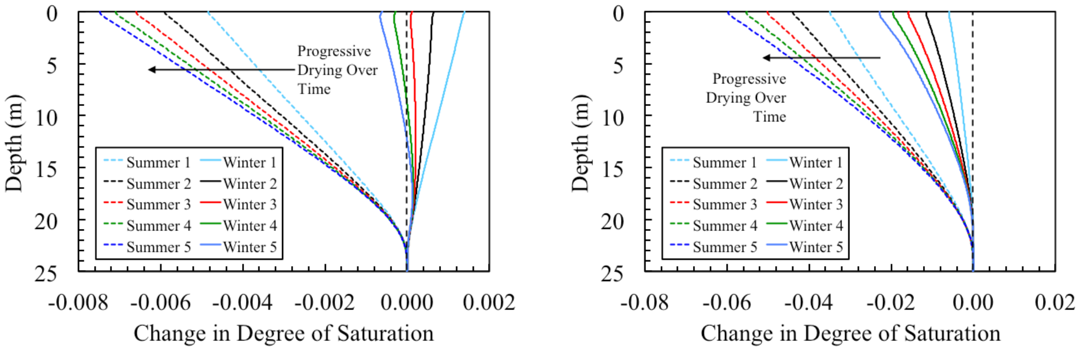
The temperature distribution within the 2-dimensional model space at various times for Case 1 is shown in Fig. 4. The temperature distribution for Case 2 is similar, albeit with greater magnitudes, so it is not shown here. On day 90, the soil was subjected to a maximum temperature of 25 °C from an initial temperature of 15 °C (initial), resulting in a fairly linear temperature distribution away from the energy pile. Continuing onto Day 180, the temperature of the foundation begins to decrease back to 15 °C. During cooling from Day 90 to 180, the initial temperature of the silt is not recovered, leaving a region of warmer soil bounded by colder temperatures. The reverse phenomenon is observed during temperature reversal.



Initial Day 90 Day 180 Day 720 Day 1260 Day 1800

Fig. 4. Temperature Contours Around the Energy Pile (Case 1)

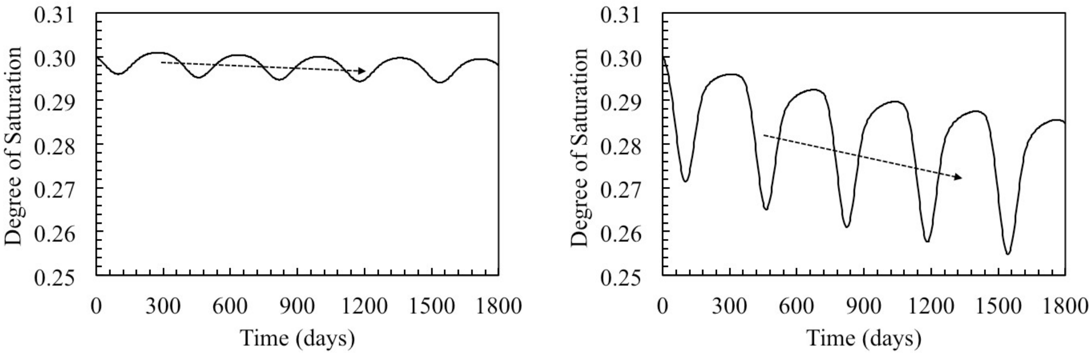
Variations in the thermal gradient with time due to thermal cycling of the energy pile will impact the movement of water within the soil profile during heating and cooling. This behavior is observed in Fig. 5Error: Reference source not found for Cases 1 and 2 where the resulting changes in saturation along the length of the energy pile is presented during the peaks of summer (25 or 45 °C applied) and winter (5 or 0 °C applied). Progressive drying is observed around the energy pile in both cases. This indicates that soils with lower initial degrees of saturation at the beginning of a temperature cycle will show greater decreases in degree of saturation due to thermally induced water flow. Comparison of the results for the two Cases indicates that nearly 10 times more drying was observed for the pile Case 2, which experienced a 20 °C greater temperature in the summer.



(a) **(b)**

Fig. 5. Changes in Degree of Saturation with Depth: (a) Case 1; (b) Case 2

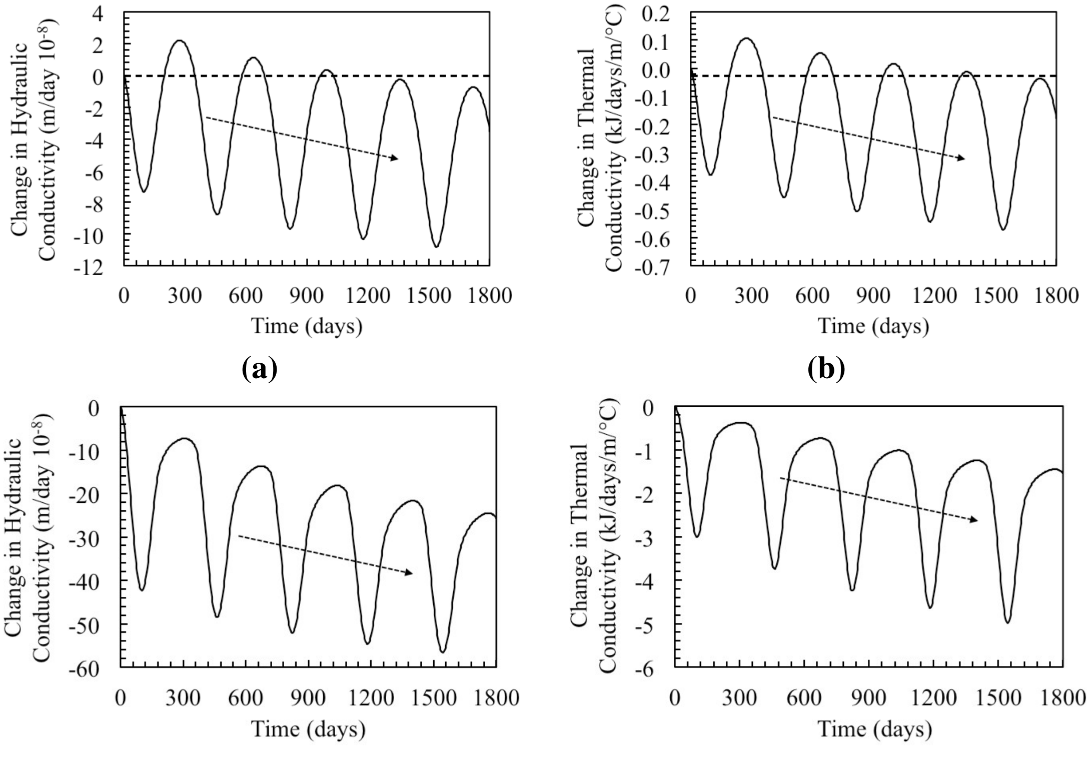
The variation in saturation at a depth of 4.8 m (corresponding to an initial degree of saturation of 0.3) with time from the start of heating is shown in Fig. 6 for Cases 1 and 2. A downward trend is observed in the degree of saturation superimposed atop the temperature cycles. The magnitude of the variation of degree of saturation appears to be greater for the exaggerated thermal cycle for Case 2. This may be due to the coupled influences of changing saturation, hydraulic conductivity, and thermal conductivity. A final decrease in degree of saturation, after 1800 days, of about 0.002 was observed for Case 1, while a decrease in degree of saturation of about 0.015 was observed for Case 2, though larger decreases are observed following summer cooling.



(a) **(b)**

Fig. 6. Variation in Saturation at a Depth of 4.8 m: (a) Case 1; (b) Case 2

For the temperature fluctuations applied, the decreases in degree of saturation were smaller than those observed by Coccia and McCartney (2013), which were as high as 0.2 for a sustained temperature boundary condition over the course of 50 days. The difference is a result of the transient change in the temperature boundary condition applied by the energy pile. The gradual temperature fluctuation will result in a small thermal gradient which may not activate a substantial flow of pore water away from the zone of highest temperature. As the degree of saturation decreases, it is expected that the values of hydraulic conductivity and thermal conductivity will also decrease. The changes in hydraulic conductivity and thermal conductivity with time at a depth of 4.8 m for Case 1 are shown in Figs. 7(a) and 7(b), respectively, and for Case 2 in Figs. 7(c) and 7(d), respectively. Differing trends for Case 1 and 2 are due to the nonlinear relationships in the SWRC, HCF and TCF. As the seasons continue to transition from summer to winter, the thermal gradient reverses, causing pore water to return to the foundation. However, due to the decreased hydraulic conductivity from the previous summer heating regiment, the initial saturation of the soil will not be fully recovered. As the unsaturated soil nearest the energy pile undergoes further temperature cycling, the process will amplify, resulting in the continuous drying trend observed in Fig. 6.



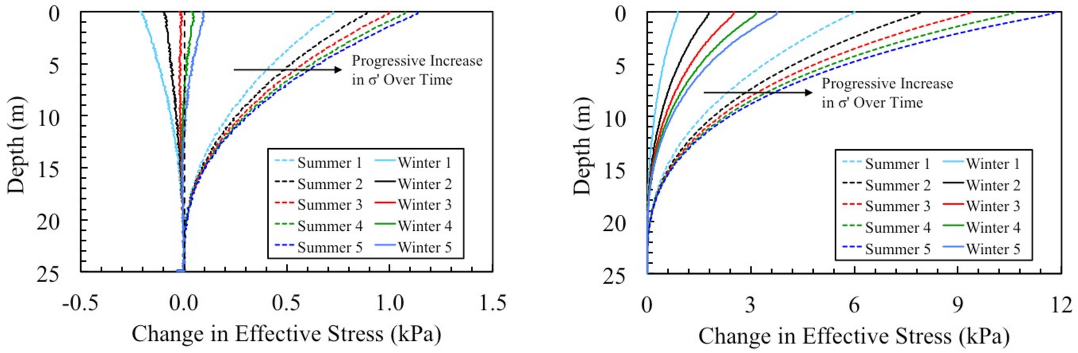
(a) **(b)**

(c) **(d)**

Fig. 7. Variations in Soil Properties at a Depth of 4.8 m: (a) Hydraulic Conductivity for Case 1; (b) Thermal Conductivity for Case 1; (c) Hydraulic

Conductivity of Case 2; (d) Thermal Conductivity for Case 2

Decreases in the degree of saturation (and increases in matric suction) will also result in increased effective stress surrounding the energy pile accordingly the Eq. (1). The change in effective stress during the peak summer and winter seasons along the depth of the foundation is shown in Fig. 8 for Cases 1 and 2. The temperature fluctuations in Case 2 led to an increase in effective stress at the head of the foundation that was nearly 10 times greater than that in Case 1. As the water table is fixed at the base, no change in effective stress was observed at this level. Increased effective stresses may result in increased skin friction, resulting in a greater ultimate load capacity with increased temperature. This may explain the increased capacity of energy piles in unsaturated silt observed by Goode and McCartney (2015), but not for energy piles in dry sand. Increases in effective stress may also cause additional settlement, leading to dragdown effects and increased axial stresses in energy piles.



(a) **(b)**

Fig. 8. Changes in Effective Stress with Depth: (a) Case 1; (b) Case 2

5. CONCLUSION

As temperature cycles are applied to energy piles in unsaturated soil layers, a gradual irreversible movement of water may occur away from the energy pile. This irreversible decrease in saturation is attributed to the coupled influences of changes in saturation, hydraulic conductivity, and thermal conductivity, which is exaggerated for higher temperature changes. For an initial degree of saturation of 0.3, the thermal conductivity of the surrounding soil decreased by 0.18 kJ/day/m/°C for Case 1 but decreased by -1.53 kJ/day/m/°C for Case 2. Soils having lower initial degrees of saturation were found to show greater drying and larger changes in hydraulic and thermal conductivity. The effective stresses in the soil around the energy pile will increase with time due to drying, which may be either beneficial or detrimental to the pile depending on the loading conditions. Nonetheless, the changes in soil behavior due to cyclic heating were not significant but be relevant in some situations.

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